Background: Short wavelength radiation has been used in medicine and materials studies since immediately after the 1895 discovery of X-rays. The development of synchrotron sources over the last ~25 years has led to a boom in applications in other areas, including environmental science. Despite the widely acknowledged advantages of synchrotron radiation, there is not enough to go round. Due to the cost of such sources this is likely to remain the case. Hence the need to develop alternative, cheaper, more accessible sources which can offer at least some of the properties of synchrotrons.

www.shortwavelengthsources.net

Objectives: To advance European research & development in laboratory scale short wavelength sources to widen access to research and analysis that currently can only be undertaken at large scale facilities such as synchrotrons and free electron lasers.

- WG1 Modelling & Simulation, giving direction to the wide range of experimental parameters that must be varied to optimise source output;
- WG2 Source Development, Improvement & Characterization, in order to provide optimum emission properties;
- WG3 Integrated Systems: Sources, Optics and Detectors, to ensure optimum use of the source output;
- WG4 Applications: the raison d'être for the developments of the above three working groups.

Results vs objectives:

Through modeling emission characteristics, we now have a much enhanced understanding of the most important source parameters (WG1).

We have identified further potential mechanisms for laboratory-scale short wavelength sources (WG2).

Improved optics and detectors, developed within the Action both as a direct result of COST funding and through national / cross-national funds raised (in part) through the support of COST. have lead to more efficient use of the source output (WG3).

The very wide range of cross-disciplinary applications which will be enabled by the work of the Action could not be envisaged by a single institution (WG4).

Some statistics:

Countries involved	16 EU, 5 non-E
Institutions involved	About 70
People involved	About 200, including 94 ESRs
WG meetings	9 for each WG
Workshops	3
Training schools	4
STSMs*	19
Total funding	About €475,000
Publications	>300 and rising
Degrees awarded	About 40 PhD and Masters
New programmes	About 10 EU, 20 national

*Short-term scientific missions.

Some sources studied either theoretically, experimentally or both:

- Microfocus
- Laser-generated plasmas
- Discharge plasmas
- Pinch plasmas
- Table-top high-rep rate EUV and soft X-ray lasers
- Capillary soft X-ray lasers
- High harmonic generation
- Thomson back-scatter
- Laser wakefield
- Transition radiation
- Carbon nanotube field emission

Some applications:

- Radiobiology
- X-ray microscopy and spectromicroscopy
- Laser ablation, surface modification
- EUVL and mask inspection
- Fluorescence imaging
- Cultural heritage (many studies)
- Environmental science
- Analysis of thin films
- Microtomography
- Optics characterisation for X-ray astronomy and EUVL
- Security

We want to study a range of problems in radiation biology:

- How are biological cells damaged by ionising radiation?

  More specifically, how is response to radiation distributed across a cell? What is a "safe" dose?

- How significant is damage to components other than nuclear DNA?

  Prior to the development of a focused X-ray microprobe some results, using *α* particles, suggested that cytoplasm damage (presumably mitochondrial DNA) may be important.

- Can damage effects be transmitted to un-irradiated cells — the bystander effect?

  Statistical analyses of experiments with unfocused X-ray beams had previously suggested that they may be.

Historically, experiments using X-rays to study radiation damage were carried out using unfocused beams.

- The low-dose responses of cells were ∴ hard to determine; with soft X-rays, the dose imparted by a few photons is damaging (1 Gy = 1 J/kg ≡ ~10 absorbed carbon K photons in a cell nucleus). But if the beam is unfocused, the precise dose to each cell is unknown.

- How is response to radiation distributed across a cell?

- How significant is damage to components other than nuclear DNA?

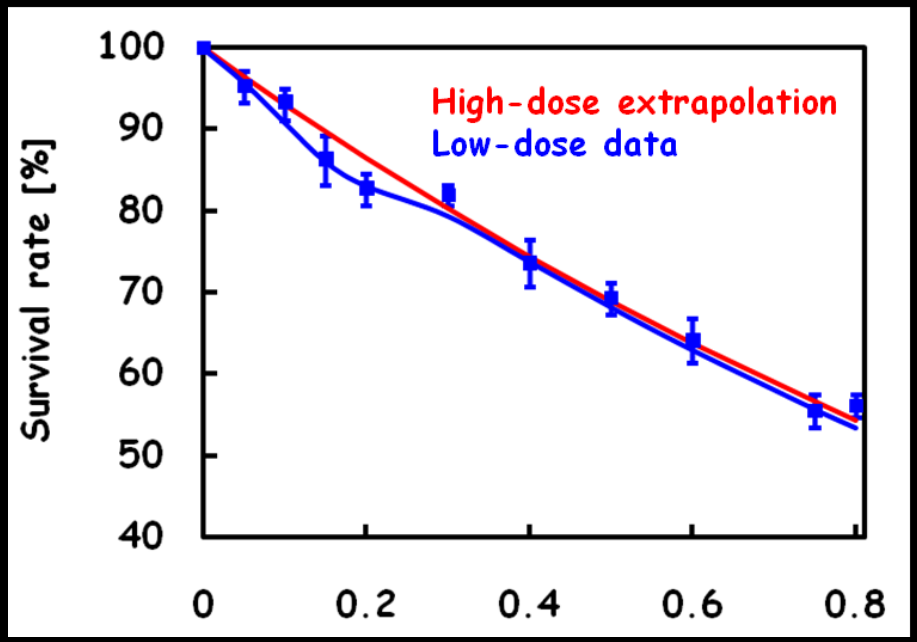
- Can damage effects be transmitted to un-irradiated cells — the bystander effect?

- Microprobing of biological cells using sub-micrometre spots of focused carbon K X-rays (284 eV) has been very successful in studies relevant to radiation-induced cancers, including:
  - Low-dose effects, including low-dose hypersensitivity (what is a safe dose?).

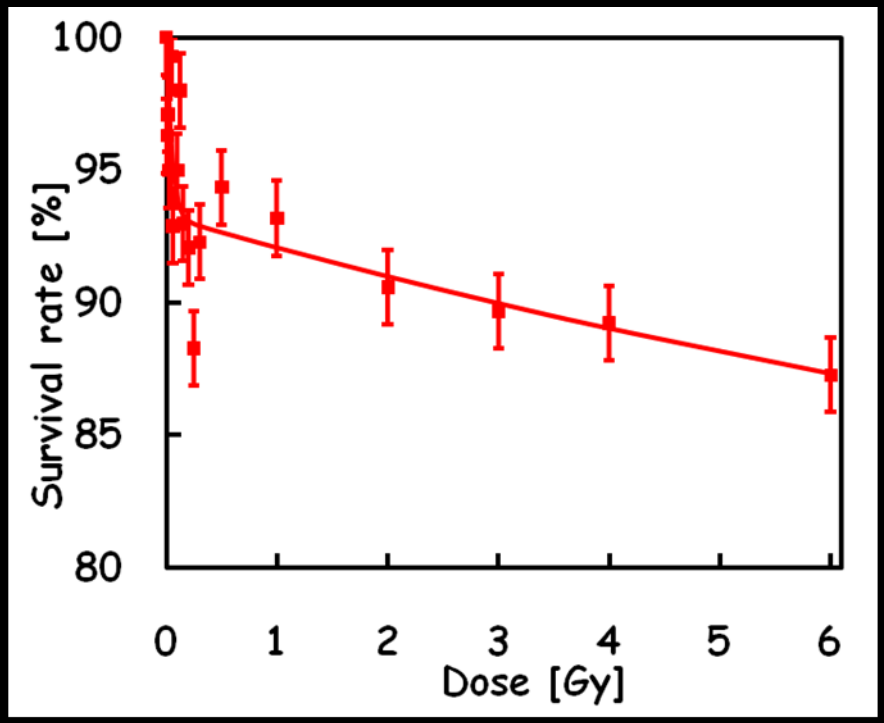
Is this a good thing or a bad thing?

What is the main source of the high dose data?

What is the third (=) highest source of radiation dose to humans?



- The bystander effect; if only one cell out of a population in a dish is irradiated, up to ~10% do not survive.

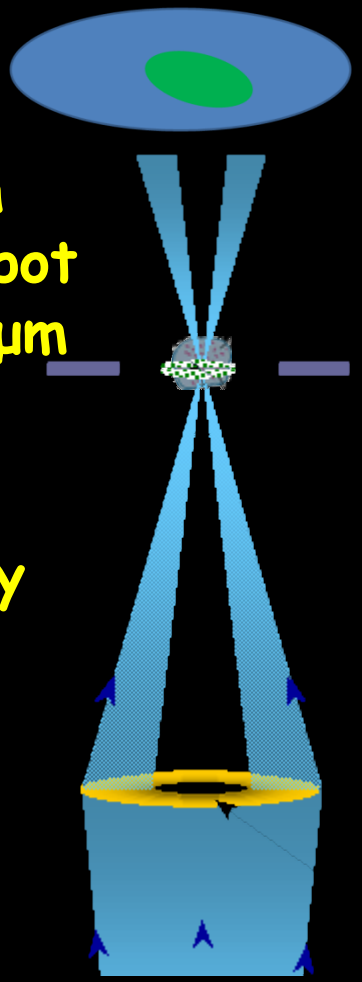


- Comparison of cytoplasm and nucleus irradiation; around the same percentage of cells seems to survive irrespective of whether the nucleus or cytoplasm is specifically irradiated. This suggests that damage to both nuclear and mitochondrial DNA is important.

☹ However, there are problems ...

- There will always be some cytoplasm irradiation even when the nucleus is targeted. Hence it is hard to disentangle the two effects — more data are needed.
- C K X-rays can only penetrate one cell; essentially zero are unabsorbed. Tissue samples, much more important for radiation effects in living organisms, cannot be studied.
- To study tissue samples higher energies are needed; Cr K_a (5.4keV) X-rays are suitable.
- So far it has only been possible to study effects related to cell death, rather than. Fortunately, mutations are much rarer; at low doses only ~1 in 10^4 cells mutate – the rest repair correctly or die. Very few of those that do mutate are potentially cancerous.

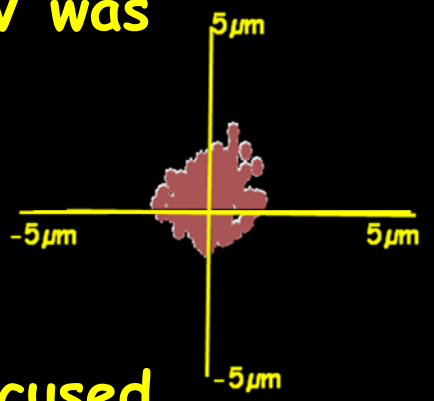
- Experiments so far have been done using zone plates, with the focal spot size limited by the source size.
- With a source size ≈5-25 µm, as obtained with the microfocus source used so far, the focal spot size is ≈0.2-1 µm for C K but would be ≈4-20 µm for Cr because of the increased focal length.
- The focused flux is limited by the monochromatic source output and the efficiency and aperture of the optic (A_{eff}~10^{-9} for a typical zone plate).



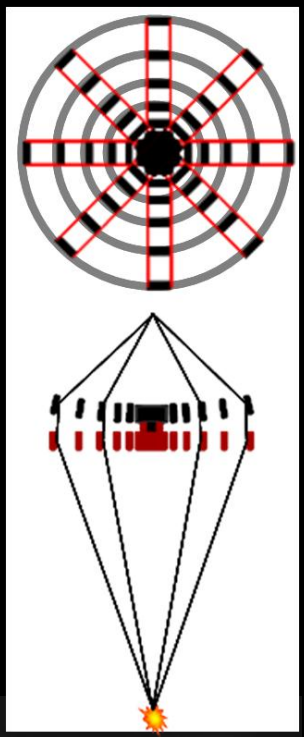
- To be able to study mutation effects in tissue samples, and to disentangle nucleus/cytoplasm effects, need some or all of:
  - ✓ higher source output;
  - ✓ smaller source size (≈1 μm);
  - ✓ higher demagnification;
  - ✓ higher efficiency and/or aperture optic —
  - ✓ all at keV energies with 24/7 access.
- These factors define the design goals of the new microfocus source and associate optics.

How can we get a 1 µm source size?

- The accelerating voltage must be low, to optimise K X-ray production, limit secondary electron range and prevent high energy Bremsstrahlung - 15 keV was selected as suitable for ~5 keV X-rays.
- This limits the beam current, to reduce divergence which would increase the electron focus size.
- FEA calculations show that ~1 mA can be focused into a ~1 µm spot, a power density of ~2×10^{13} W/m^2.
- The original plan was a Ti target (4.5 keV), but at such a power density Ti will melt (FEA), even with cooling, due to its low melting point (1935 K) and conductivity (22 W/m/K).
- Instead use liquid N_2 cooled (?) chromium, melting point 2180 K and thermal conductivity 94 W/m/K.

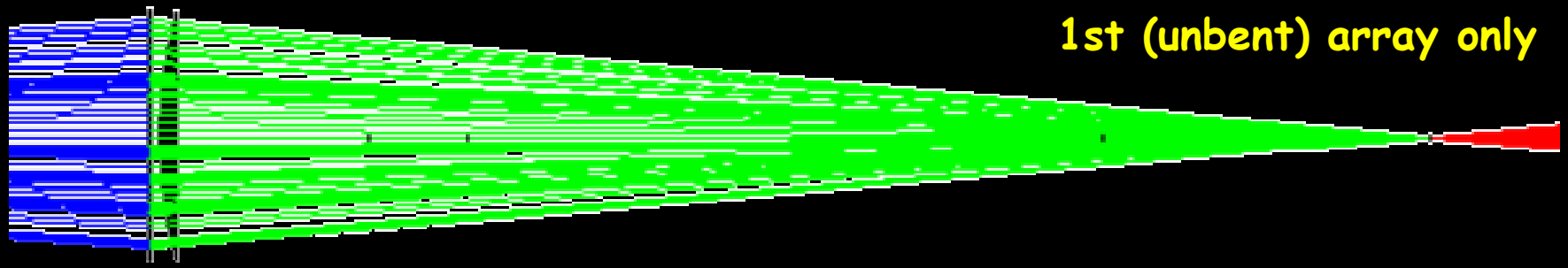


Improving the Optics: Micro-Structured Optical Arrays

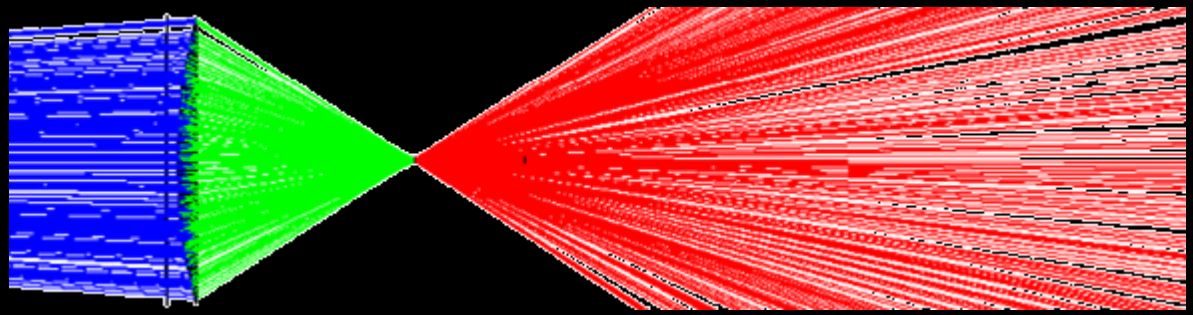


- Arrays of channels etched into silicon.
- By using single grazing incidence reflections in each of two arrays aberrations can be reduced.
- Bending the arrays can reduce aberrations further and give variable focal length.
- Prototype design for 5.4keV:
  - 10µm channels, 20µm period
  - 2mm diameter (2mm square for 1D prototype)
  - 50-200µm thick silicon
  - second component bending radius ≈5cm
  - focal length ≈5cm.
- With ≈1nm (AFM measurement) sidewall roughness this gives over 100× as much focused flux as a typical zone plate - even more if Bremsstrahlung can be used.

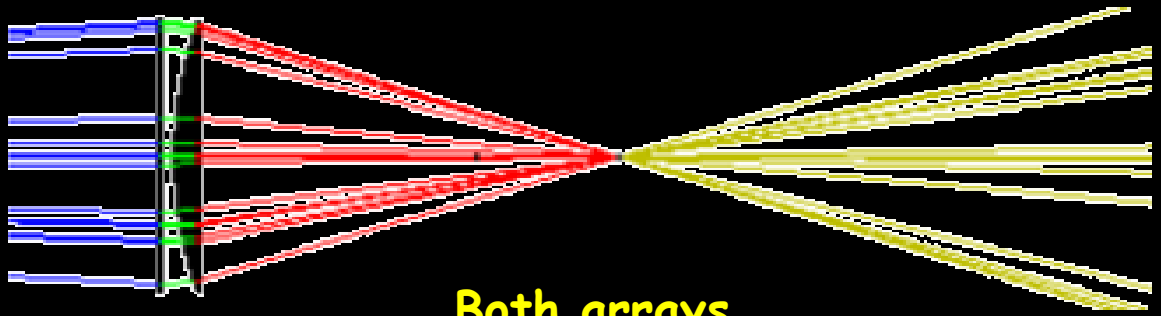
Improving the Optics: Micro-Structured Optical Arrays



1st (unbent) array only



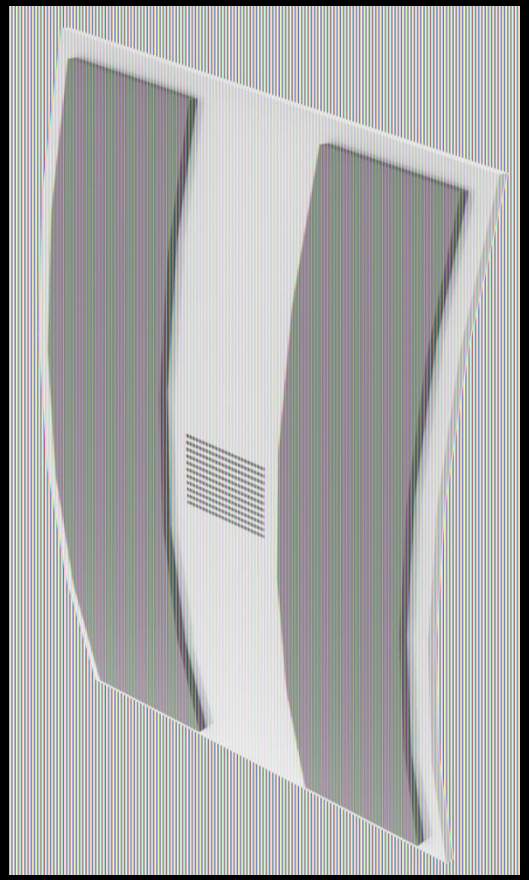
2nd (bent) array only

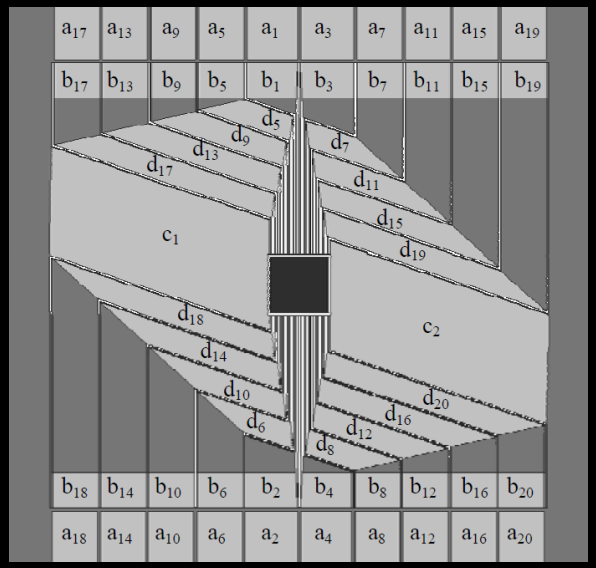


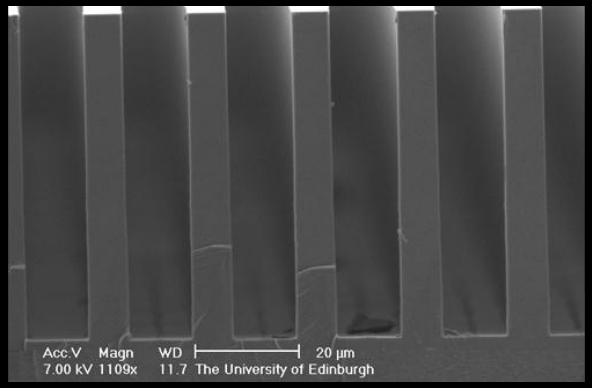
Both arrays

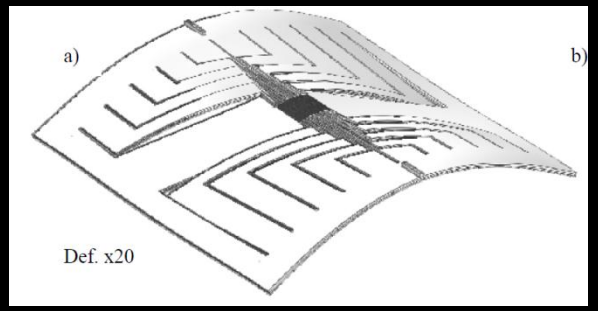
Focal spot size:
≈0.3 µm (point source)
≈0.35 µm (1 µm source)
≈2× smaller than for a single reflection
≈2.5× smaller than for a typical zone plate

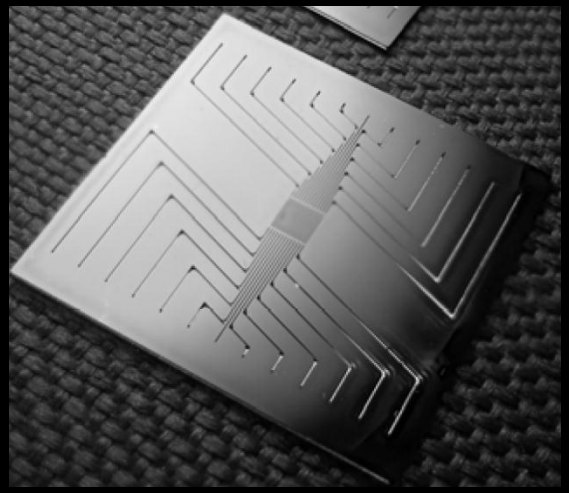
Improving the Optics: Micro-Structured Optical Arrays

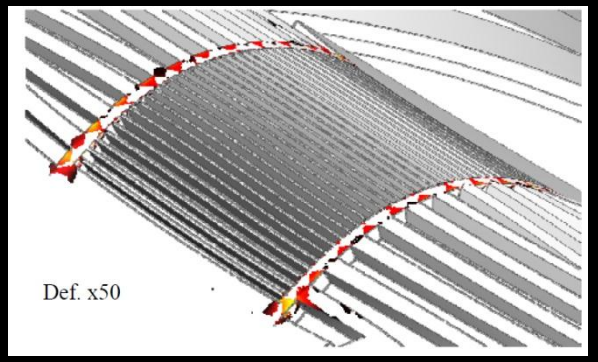






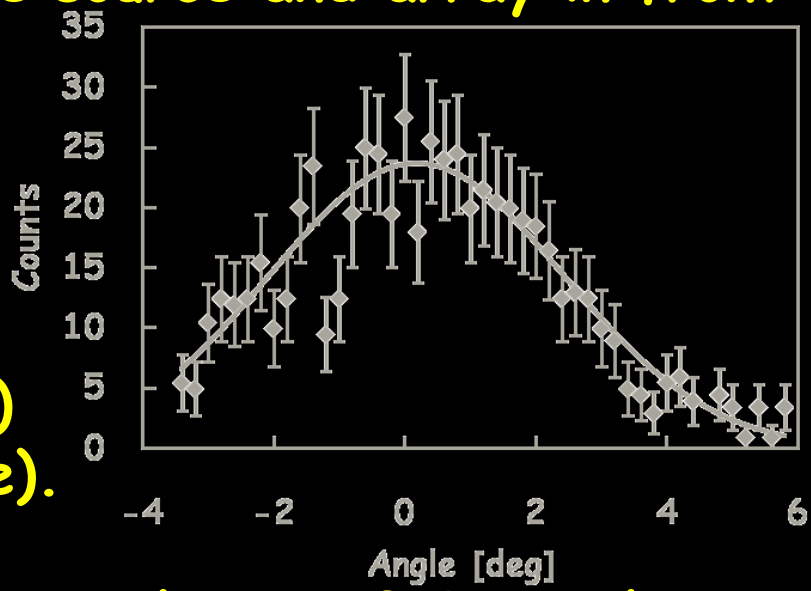






Improving the Optics: Micro-Structured Optical Arrays

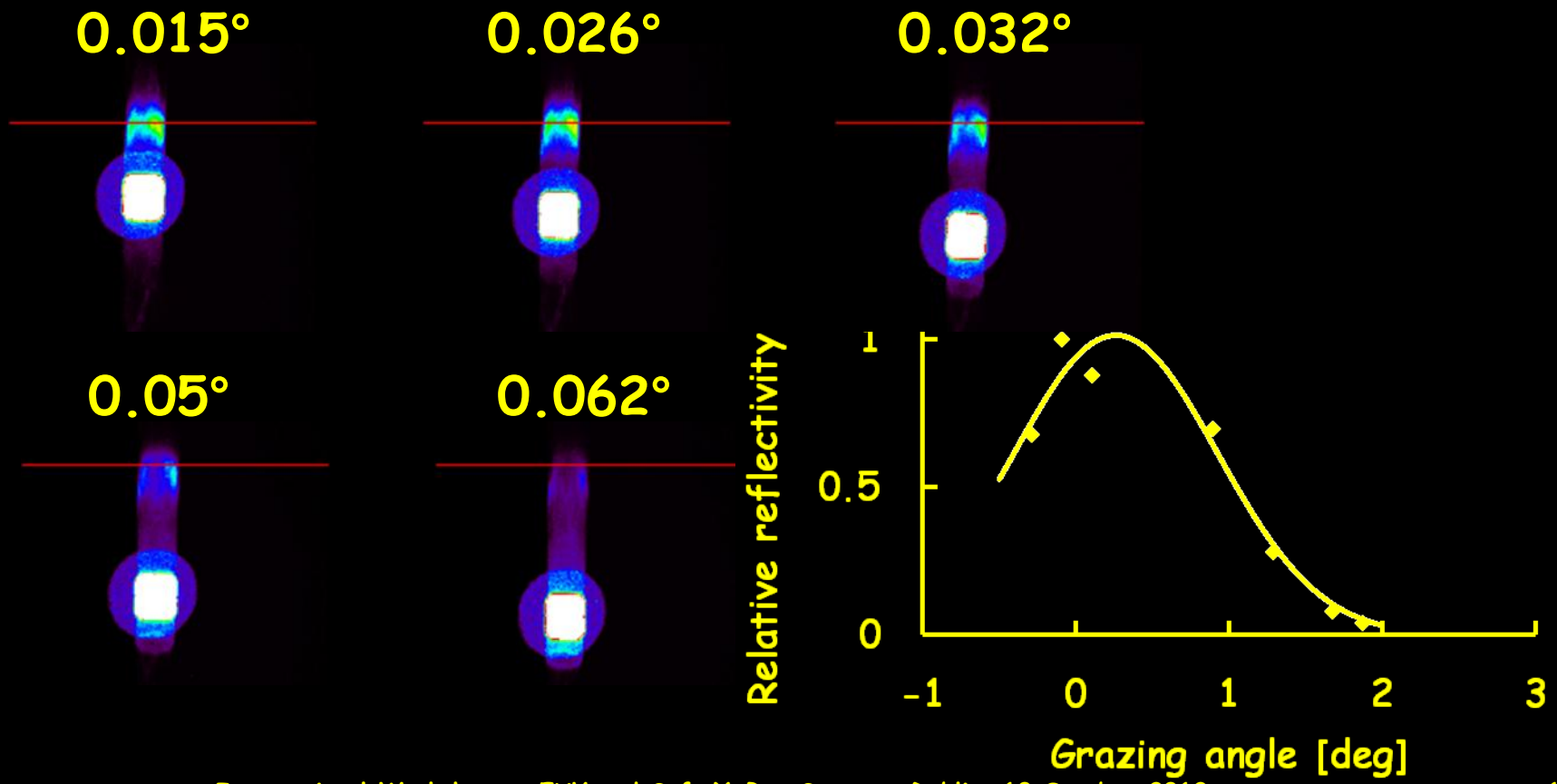
- The reflectivity of an etched array was measured at ≈500eV by relatively rotating the source and array in front of a CCD.
- 0° is the angle at which most X-rays should be reflected. Away from 0° the count rate falls since more X-rays pass straight through (negative angles) or are multiply reflected (positive).



- Reflectivity was expected over a range of ≈5°. The fitted Gaussian peak is at 0.2°, with a FWHM of 5.3°.
- The peak reflectivity is a few percent (at a much larger glancing angle than will be used in practice), consistent with the measured channel wall roughness.

Improving the Optics: Micro-Structured Optical Arrays

Reflection from a single array has also been demonstrated using the King's microfocus source with an aluminium target (K_α 1.5keV).



Summary

☺ Soft X-ray microprobes have demonstrated their use in studying a range of problems in radiation biology of single cells.

☹ But to extend these studies to mutation effects in tissue samples, it is necessary to:

❶ Use higher energy X-rays;

❷ Deliver more focused flux.

☺ It seems feasible that these goals can be achieved by:

❶ Using a chromium microfocus source with a ≈1 μm source size;

❷ Using microstuctured optical array optics, with A_{eff}>100x that of a typical zone plate.

The Future

EXTATIC

Extreme-ultraviolet & X-ray Technology And Training for Interdisciplinary Cooperation

COST MP1203

Advanced Spatial and Temporal X-ray Metrology

Kick-off: Brussels, 16 November

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